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We investigate the photoluminescence (PL) properties of a thick InGaN single quantum well (SQW) in which an AlGaN δ layer is embedded. The δ layer offers an extra degree of freedom which may be employed to tune the emission wavelength. One of the most salient features of such a QW structure is that the long-wavelength tuning is feasible with lower indium composition. The δ layer also increases the wave function overlap between holes and electrons, shortening the PL lifetime. All the measurement results are consistent with the numerical predictions. The QW structure could be of great importance in the design of long-wavelength lasers. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2205731]

The wide-band-gap III-nitride semiconductors have attracted much attention for many applications including lighting,[1,2] optical storage, medical applications, etc.[3] Through extensive studies over the past decades, it has been found[3] that such materials suffer low quality of crystal due to high dislocation densities and strong piezoelectric field effects induced by large lattice mismatch, all of which have much of an impact on the performance of light-emitting devices. With state-of-the-art growth technologies, the effects of those inherent material properties can be reduced. But even so, much care is taken to design an InGaN-based quantum well (QW) structure for long-wavelength (i.e., green and red) light-emitting devices that are highly demanded for full-color displays. One has to inevitably increase the QW thickness and/or the indium content for long-wavelength tuning. However, the strong piezoelectric field reduces considerably the oscillator strength in thick QWs,[4] lowering the internal quantum efficiency. On the other hand, several defects such as *V* defects, stacking faults, and dislocations[5] are parasitic in QWs with high indium content, which cause high nonradiative recombination. As a result, the threshold current density increases with increasing emission wavelength in laser diodes.[6] It was so high that the cw operation could not be achieved beyond 475 nm.[7] Such defect centers appearing in light-emitting diodes (LEDs) also give rise to high sensitivity of device performances to the temperature.[8]

To tackle such problems, we propose a QW structure that shortens the photoluminescence (PL) lifetime and needs lower indium composition for long-wavelength tuning. It is based on a thick InGaN single quantum well (SQW) in which an AlGaN δ layer is embedded. A similar structure with GaInAs–GaAs strained-layer double QWs has been investigated.[9] In this letter, we study exclusively the PL properties of the QW structure by time-resolved photoluminescence (TRPL) spectroscopy. For a systematic inquiry, we have solved Poisson's equation and the effective-mass Schrödinger equation self-consistently. The numerical calculation of the band structure offers a clear understanding as to the underlying physics of the QW structure.

InGaN/GaN SQWs were grown on (0001) sapphire substrates by metal-organic vapor phase epitaxy (MOVPE). In the QW structures, a 1-nm-thick AlGaN δ layer is embedded in the center of a 5-nm-thick InGaN SQW (i.e., 2 nm $In_{0.16}Ga_{0.84}N$–1 nm $Al_{0.05}Ga_{0.95}N$–2 nm $In_{0.16}Ga_{0.84}N$). Thus, the total well thickness is measured to be 4 nm by the x-ray rocking curve analysis. The AlGaN δ layer was grown at the same growth temperature as the InGaN SQW. Low (740 °C) and high (1320 °C) temperature deposited GaN buffer layers were used to improve the quality of upper-grown barriers and QWs. The samples have an undoped SQW that is sandwiched between 6.2-nm-thick GaN barriers. In the PL measurement, they were excited with 1.5 ps pulses from a frequency-doubled Ti:sapphire laser. The laser wavelength is 400 nm and the repetition rate is 80 MHz. All measurements were done at 13 K.

Shown in Fig. 1(a) are the calculated energy band profile and first (lowest) subband wave functions of the 5-nm-thick $In_{0.16}Ga_{0.84}N$ SQW sandwiched between 10-nm-thick GaN barriers. For this calculation, Poisson's equation[10] is solved together with the Schrödinger equation based on the 6×6 effective-mass Hamiltonian.[11,12] The finite difference approach is employed for the spatial discretization and the in-

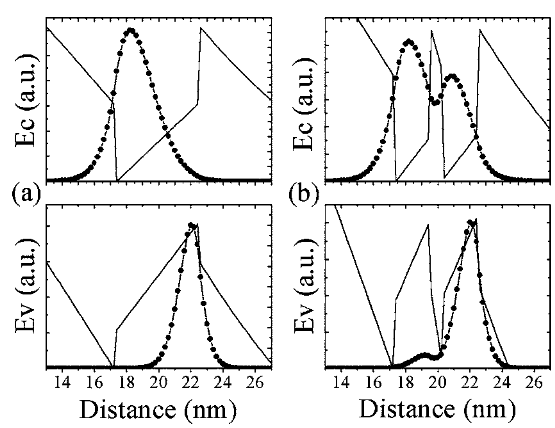

FIG. 1. Energy band profile and wave function of (a) 5-nm-thick $In_{0.16}Ga_{0.84}N$ SQW and (b) $In_{0.16}Ga_{0.84}N$ (2 nm)–$Al_{0.05}Ga_{0.95}N$ (1 nm δ layer)–$In_{0.16}Ga_{0.84}N$ (2 nm) QW sandwiched between 10-nm-thick GaN barriers under zero bias current.

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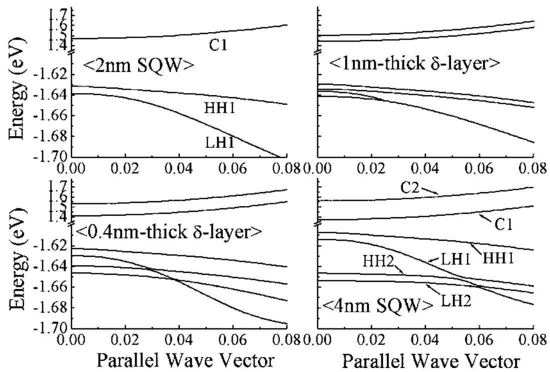

FIG. 2. The in-plane dispersion of conduction and valence subbands of 2-nm-thick $In_{0.16}Ga_{0.84}N$ SQW, $In_{0.16}Ga_{0.84}N$ QW with embedded 4-Å- and 10-Å-thick $Al_{0.05}Ga_{0.95}N$ δ layers, and 4-nm-thick $In_{0.16}Ga_{0.84}N$ SQW.

verse power method is used to solve the eigenvalue problem. The band-offset ratio $(\Delta E_c/\Delta E_v)$ of InGaN/GaN and AlGaN/GaN is assumed to be 0.7/0.3 and 0.67/0.33, respectively.[13,14] The strain effects are considered[11,12] and the piezoelectric sheet charge density at the interfaces between a QW and a barrier is incorporated.[10] It is apparent that the electrons and holes are spatially localized (separated) and thus the wave function overlap between them is considerably decreased due to the strong piezoelectric field. In the proposed QW structure, however, it can be increased by the embedded AlGaN δ layer, as evident in Fig. 1(b). The electron wave function is further extended toward the n side (right-hand side of the diagram) and the hole wave function to the p side of the QW,[9] the transition probability (PL lifetime) by which is expected to increase (shorten). We shall return to this point later with the measured result of the PL lifetime.

To clearly understand the optical behaviors of the QW structures with different δ-layer thicknesses, we have further calculated their conduction and valence band structures and presented the results in Fig. 2. For a comparative study, the band structures of 2-nm- and 4-nm-thick $In_{0.16}Ga_{0.84}N$ SQWs without a δ layer are also shown. One can see that the lowest conduction subband ($C1$) of the 2-nm-thick SQW is split into two subbands in the QW with the δ layer. The separation increases as the δ-layer thickness decreases. Eventually, those separated subbands become the subbands ($C1$ and $C2$) of the 4-nm-thick SQW when the δ-layer thickness is zero. Similar phenomenon, known as the effect of well coupling, also happens in the valence band. The $C1$-HH1 transition energy of the QW structure is reduced with decreasing δ-layer thickness and always lies between or rather bounded by the transition energies of those 2-nm- and 4-nm-thick SQWs. This numerical prediction is in qualitatively good agreement with the measured results in Fig. 3, showing the low-temperature luminescence spectra of 2-nm-thick $In_{0.16}Ga_{0.84}N$ SQW, $In_{0.16}Ga_{0.84}N$ (2 nm)–$Al_{0.05}Ga_{0.95}N$ (1 nm)–$In_{0.16}Ga_{0.84}N$ (2 nm) QW, and 4-nm-thick $In_{0.16}Ga_{0.84}N$ SQW. As expected, the PL peak wavelength (=485 nm) of the QW with the δ layer lies between that (454 nm) of the 2-nm-thick SQW and that (=520 nm) of the 4-nm-thick SQW. We can therefore conclude from these that by adjusting the δ-layer thickness, one can obtain the desired PL peak wavelength within the wavelength range determined by those 2-nm-thick (half-thick) and 4-nm-thick (same-thick) SQWs without a δ layer.

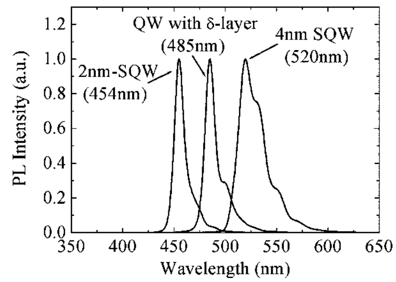

FIG. 3. Low-temperature (13 K) cw PL spectra of nominally undoped 2-nm-thick $In_{0.16}Ga_{0.84}N$ SQW, $In_{0.16}Ga_{0.84}N$ (2 nm)–$Al_{0.05}Ga_{0.95}N$ (1 nm)–$In_{0.16}Ga_{0.84}N$ (2 nm) QW, and 4-nm-thick $In_{0.16}Ga_{0.84}N$ SQW.

Figure 4 shows the luminescence decay dynamics measured at the emission peaks in the spectra (in Fig. 3) by TRPL spectroscopy. Through a curve fitting, the PL lifetime of 2-nm-thick $In_{0.16}Ga_{0.84}N$ SQW, $In_{0.16}Ga_{0.84}N$ (2 nm)–$Al_{0.05}Ga_{0.95}N$ (1 nm)–$In_{0.16}Ga_{0.84}N$ (2 nm) QW, and 4-nm-thick $In_{0.16}Ga_{0.84}N$ SQW is estimated to be 13.2, 104, and 450 ns, respectively. As expected from the numerical result in Fig. 1, the PL lifetime of the QW structure with the δ layer is considerably shortened due to the increased wave function overlap, compared to the 4-nm-thick $In_{0.16}Ga_{0.84}N$ SQW. The same behavior as observed in the PL intensity spectra is also shown in the luminescence decay dynamics, namely, the PL lifetime of the QW structure varies depending on the δ-layer thickness within the lifetime range determined by those 2-nm-thick (half-thick) and 4-nm-thick (same-thick) SQWs.

To make a direct comparison at the same PL peak wavelength (green wavelength around 520 nm), we have further increased the In mole fraction of the 2-nm-thick SQW and the QW with the δ layer and measured their PL decay dynamics shown in Fig. 5. It is actually expected from Fig. 3 that the QW structure with the δ layer requires lower indium composition for long-wavelength tuning. Through the x-ray rocking curve analysis, the indium content of the 2-nm-thick SQW grown at 950 °C is shown to be about 5% higher than that of the QW structure with the δ layer at 990 °C. The PL lifetime of the 2-nm-thick SQW is changed little (almost the same as that in Fig. 4) due probably to its very small QW thickness. This may indicate that the effect of an increase in strain-induced piezoelectric charge on the PL decay dynamics is not so pronounced in a thin QW. However, the crystal quality would be much deteriorated due to high indium content, which is the root cause for high threshold current density of long-wavelength laser diodes.[7] In the QW structure with the δ layer, on the other hand, the PL lifetime is in-

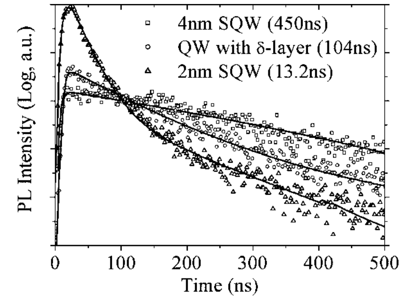

FIG. 4. Logarithmic plot of PL decay dynamics measured at the emission peaks in Fig. 3.

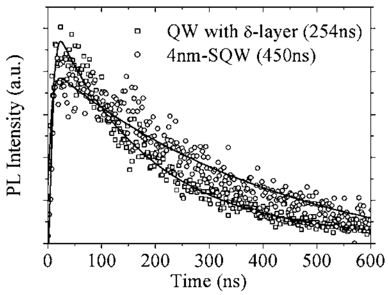

FIG. 5. Low-temperature (13 K) PL decay dynamics of the 4-nm-thick SQW and the QW structure with the δ layer around the PL peak wavelength of 520 nm.

creased to 254 ns, but still much shorter than that of the 4-nm-thick SQW.

We have further measured the PL intensity spectra for different δ-layer thicknesses emitting in the green wavelength region, as shown in Fig. 6. In accordance with a conclusion made earlier, the transition energy (PL peak wavelength) of the QW structure is reduced (increased) with decreasing δ-layer thickness.

In summary, we have investigated the photoluminescence properties of a thick InGaN SQW where an AlGaN δ layer is embedded. The emission wavelength depends sensitively on the δ-layer thickness, which offers an extra degree of freedom in tuning the emission wavelength. We have demonstrated that the QW structure with the δ layer needs a smaller amount of indium for long-wavelength tuning compared to the half-thick SQW, and has shorter PL lifetime or rather larger wave function overlap compared to the same-thick SQW. All the measurement results are consistent with the numerical predictions. In reality, the lowest threshold current was obtained with two InGaN QWs for near 400 nm lasers[15] and with a SQW for laser emission longer than 435 nm.[6] What is worse, as aforementioned, no lasing oscillation was generated beyond 475 nm due to the poor crystal quality induced by high indium content.[7] In the case where a thin SQW has to be used, the temperature and the current overflow in the active region would be issues for high current injection.[16] With the proposed QW structure, however, one may be released from those and reduce the threshold current density of green lasers as lower indium composition is required in the QWs.

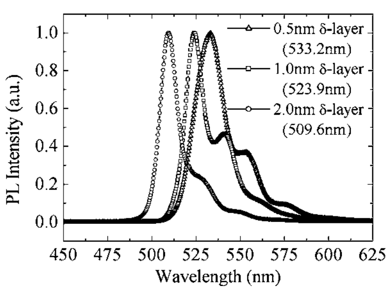

FIG. 6. Low-temperature (13 K) cw PL spectra of the QW structures with different δ-layer thicknesses.

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